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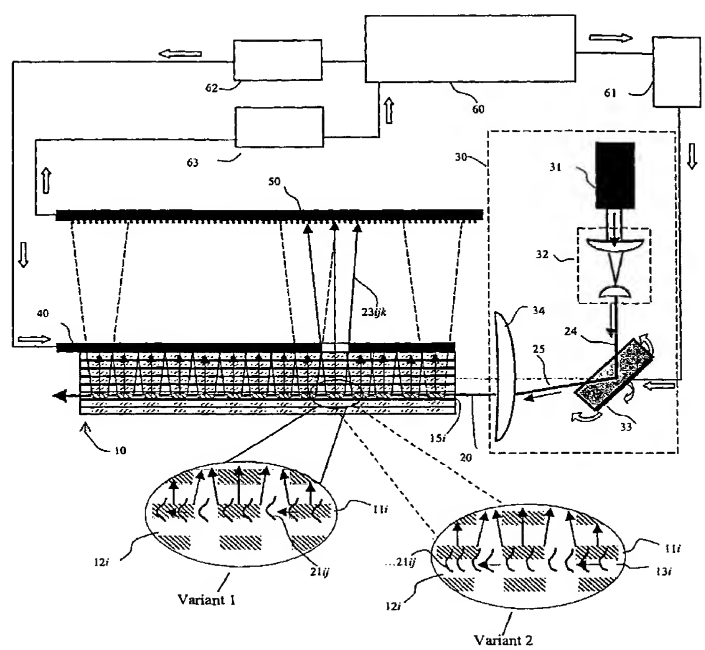
(54) Title: WAVEGUIDE MULTILAYER HOLOGRAPHIC DATA STORAGE



(57) Abstract: The invention provides a method and apparatus for providing a high information capacity, high data rate and short access time simultaneously. The method and apparatus include a multilayer waveguide holographic carrier, a multilayer waveguide holographic data storage system, a multilayer waveguide hologram reading method with random data access, and a process and apparatus for recording matrix waveguide hologram layers and assembling a multilayer carrier.

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WAVEGUIDE MULTILAYER HOLOGRAPHIC DATA STORAGE

FIELD OF THE INVENTION

The present invention relates to volume holographic data storage and more particularly, to waveguide multilayer holographic data storage systems for providing a high throughput of data storage.

BACKGROUND

The logic of evolution of modern information technologies dictates a necessity to create data storage systems with a high information capacity, a high data rate and small access time, i.e. a high throughput system. Many researchers use the CRP (capacity-rate product) factor for the throughput estimation where CRP = Capacity [GB] x Data Rate [Mbps] (High Throughput Optical Data Storage Systems *An OIDA Preliminary Workshop Report* April 1999. Prepared for Optoelectronic Industry Development Association by Tom D. Milster).

A more objective factor, being proposed for use in this invention, is CARP (capacity-access-rate product), which is the capacity in GB, divided by access time in ms and multiplied by the data rate in Mbps. We have CARP = {C [GB] / A [ms]} x Data Rate [Mbps]. A comparison of CARP factors gives the possibility to estimate objectively the advantages of any data storage system in terms of throughput.

It is clear that a need exists for systems in future applications where CRP>10^5 and CARP> 10^6. That is, for example, a memory system with >1GB information capacity, >100Mbps data rate and <1ms access time. At the same time, it is clear that it is necessary to ensure a minimum quality of recorded and readout signals, that is to provide a desired value of the signal/noise ratio and thereby to maintain a desired value of the error probability.

Holographic methods are considered the most prospective for high throughput data storage. More specifically, the data page oriented random access holographic memory is in the first place as a high throughput system. However, there have been difficulties and problems in the development of the high throughput system up to the present day. The high data rate for optical data storage systems depends on the light source power, sensitivity of photodetector, the number of information parallel input-output channels, and also on the conveying speed of the carrier or optical reading head, when using a design with moving mechanical parts.

For holographic storage a large number of parallel data channels is provided due to data presentation as two-dimensional pages of digital binary or amplitude data. Moreover, the highest data rate is provided when there are no moving mechanical parts, such as a rotating disk carrier.

Short random access time of a memory system is a result of applying a high-speed addressing system such as electro- or acousto-optical deflectors and using a recording-reading schema, which provides for transferring read images from different microholograms to a photodetector without any mechanical movement.

Use of a volume information carrier in optical (including holographic) data storage for providing a high information capacity and high information density is well known, as in United States Patent 6,181,665 issued January 30, 2001 to Roh. But existing methods of optical (holographic) data storage based on a volume carrier do not obtain high capacity and short random access time simultaneously in accordance with the circumstances indicated below.

There are several methods of volumetric holographic carrier applications. The first is using angle multiplexed

volume holograms, which provide for the superimposing of data pages of Fourier or Fresnel holograms in the volume photorecording medium. Each of the holograms is recorded with a separate angle of the reference beam. The same angle of the readout beam is required for data page reading. Examples include Roh, United States Patent 6,072,608 issued June 6, 2000 to Psaltis et al., United States Patent 5,896,359 issued April 20, 1999 to Stoll, and United States Patent 5,696,613 issued December 9, 1997 to Redfield et al.

A second method is using encrypted holograms for holographic data storage as in United States Patent 5,940,514 issued August 17, 1999 to Heanue et al. In the Heanue system orthogonal phase-code multiplexing is used in the volume medium and the data is encrypted by modulating the reference beam.

This method has a number of limitations. The main problem is a deficiency of the volumetric medium in meeting the necessary requirements. For example, ferroelectric crystals do not exhibit sufficiently great stability, and photopolymers have too large a shrinkage factor.

A third method is using holograms recorded in a multilayer medium as described by "Holographic multiplexing in a multilayer recording medium", Arkady S. Bablumian, Thomas F. Krile, David J. Mehrl, and John F.Walkup, *Proc. SPIE*, Vol.3468, pp. 215-224 (1998) and by Milster. One or more holograms (a hologram matrix) are recorded in each layer of the volume carrier. A readout of each hologram is made by a separate reading beam. A limitation of this method is a low layer count, the number of layers being limited by the noise from neighboring holograms located on other layers.

The last method is using waveguide multilayer holograms. See "Medium, method, and device for hologram

recording, and hologram recording and reproducing device", Mizuno Shinichi (Sony Corp.) JP09101735A2, Publication date: April 15, 1997. Waveguide holograms are recorded in thin films of a multilayer carrier. Known methods of multilayered waveguide hologram recording and reading do not provide a high data density and small access time simultaneously.

The analysis of known methods and apparatus in the field of holographic data storage permit to draw a conclusion: at the present time there is no high throughput holographic data storage system approach providing a high value of the CARP factor.

It is an objective of this invention to provide a holographic storage system with a high CARP factor.

SUMMARY

The present method offers an integrated approach to solving a problem of providing a high information capacity, high data rate and short access time simultaneously. The required characteristics of a system are provided by a tightly bounded information carrier construction technique and new methods of data accessing, reading and recording.

The present invention includes a multilayer waveguide holographic carrier, a multilayer waveguide holographic data storage system, a multilayer waveguide hologram reading method with random data access, and a process and apparatus for recording matrix waveguide hologram layers and assembling a multilayer carrier.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention itself both as to organization and method of operation, as well as objects and advantages thereof, will become readily apparent from the following detailed description when read in connection with the accompanying

drawings:

FIG.1a shows a multilayer waveguide holographic carrier with end surface couplers for a reference beam;

FIG.1b shows a multilayer waveguide holographic carrier with diffraction grating couplers for a reference beam;

FIG.2a illustrates a method of putting a reference beam into a waveguide layer of a data storage carrier through an end surface coupler and radiation from reconstructed holograms;

FIG.2b illustrates a method of putting a reference beam into a waveguide layer of data storage carrier through a diffraction grating coupler and radiation from reconstructed holograms;

FIG.3 shows a data page image pattern to be stored holographically in a focusing plane;

FIG.4 shows a hologram layer with a superimposed hologram;

FIG.5 illustrates a system with random data access for retrieving holographically stored data from a multilayer waveguide carrier;

FIG.6 illustrates a geometrical relationship between waveguide holograms in a hologram layer and a photodetector array;

FIG.7 illustrates a system for retrieving holographically stored data from a multilayer waveguide carrier utilizing a phase conjugate reference beam;

FIG.8 illustrates a system for superimposed waveguide hologram reading;

FIG.9 illustrates a system for encrypted waveguide hologram reading;

FIG.10 illustrates a system for waveguide hologram reading by a laser matrix;

FIG.11 represents a schematic view of a process and apparatus for recording a matrix of waveguide Fourier (quasi Fourier) holograms in a photorecording layer by using a diffraction grating coupler;

FIG.12 represents a schematic view of a process and apparatus for recording a matrix of waveguide Fourier (quasi Fourier) holograms in a photorecording layer by using SLM disposed in a convergent beam;

FIG.13 represents a schematic view of a process and apparatus for recording a matrix of waveguide Fourier (quasi Fourier) holograms in a photorecording layer by using a random phase mask;

FIG.14 represents a schematic view of a process and apparatus for recording a matrix of waveguide Fourier (quasi Fourier) holograms in a layer by using a small angle input of a reference beam;

FIG.15 represents a schematic view of the single layer matrix waveguide Fresnel hologram recording process and apparatus; and

FIG.16 illustrates a system for multiplexed waveguide hologram recording.

DETAILED DESCRIPTION

Multilayer holographic data storage carrier

FIGS. 1a and **1b** show a multilayer holographic waveguide data storage carrier **10**. It comprises layer groups each

containing a hologram layer **11*i*** where ***i*** is the current layer index and cladding layer **12*i***. Holograms **14*ijk*** are located along row axis **01*ij*** where ***j*** is the current row index and ***k*** is the current hologram index. Holograms are non-overlapping in each of the rows.

In the first variant shown in **FIG. 1a**, hologram layer **11*i*** in each group is at the same time a waveguide layer having end surface coupler **15*i***. In the second variant shown in **FIG. 1a**, the hologram layer **11*i*** and waveguide layer **13*i*** with a diffraction grating coupler **16*i*** (seen in **FIG. 1b**) in each of the groups are made separately and attached to each other with an optical contact therebetween to provide transmission of the guided wave into the hologram layer. In both variants there is a cladding layer on the outer surface of the waveguide layer, with a similar function to prior art cladding layers.

In **FIGS. 1a** and **1b** $\boldsymbol{h}_{=}$ is the size of a hologram in the row direction and $\boldsymbol{d}_{=}$ is the pitch of a hologram in the row direction. $\boldsymbol{h}_{\perp}$ and $\boldsymbol{d}_{\perp}$ are the size and pitch of the holograms respectively in the transverse direction. ***h*** is the thickness of a hologram layer and ***d*** is the pitch of the layers.

As shown in **FIGS. 2a** and **2b,** a readout beam **20** penetrates into a waveguide layer through coupler **15*i*** (or **16*i***). Then, the readout beam propagates along respective row ***ij*** as a guided wave **21*ij*** and reconstructs radiation beams **22*ijk*** from all its holograms simultaneously. Reconstructed radiation from each hologram propagates towards an output surface **02** and is restricted in its spatial angle γ.

When holograms have a specified spatial angle γ *of* radiation, the hologram pitch $\mathbf{p}_{=}$ between adjacent holograms is established so as to provide an intersection of said radiation at plane **03** and in the area above this plane. All reconstructed radiation beams form focused data page images at parallel plane **04**.

FIG.3 shows a data page image pattern **51** in the focusing plane **04**. Data pixels **17*mn*** have sizes $s_{=}$, $s_{\perp}$ and pitches $t_{=}$, $t_{\perp}$ and are disposed as a 2-D matrix. **m** and **n** are current pixel indices along rows and columns respectively. All data page images have the same orientation. ***M*** and ***N*** are quantities of data pixels in the respective direction.

FIG.4 shows a hologram layer with superimposed holograms. The angle between non-parallel row axes **01*ij*** and **01′*ij*** is α. Some holograms relating to different non-parallel intersecting rows are recorded so to be at least partially superimposed. The angle between any of two nearest non-parallel hologram rows is established to be not less than the angle selectivity of said superimposed holograms.

<u>Readout method and system</u>

FIG.5 illustrates a system for retrieving holographically stored data from the multilayer waveguide carrier. The system includes a multilayer holographic waveguide data storage carrier **10** and a layer and row access unit **30**. The layer and row access unit **30** is made up of a laser **31** for generating a beam of coherent radiation and a beam former **32** for forming a beam **24**, which is deflected by angular deflector **33** and becomes beam **25** passing through an optical element(lens) **34** to a selected layer **11*i*** and, through the respective coupler **15*i*** (or **16*i***), into the selected layer along the required hologram row.

A hologram access unit **40** made in the form of a "moving window" is arranged in the region between planes **02** and **03** (see **FIG.2a**) and intended for separating radiation **22*ijk*** from any hologram **14*ijk*** to gain access thereto and block radiation from other reconstructed holograms.

A multielement photodetector **50** faces towards the output surface **02** of the carrier, intended for receiving reconstructed radiation **22*ijk*** from said hologram, disposed at plane **04** of focus of this radiation and optically coupled with a pixel pattern **51** (see **FIG.3**) of data stored by the hologram.

Lastly, a computer **60** is connected through respective interface units to control inputs of the layer and row access unit **61**, hologram access unit **62** and the photodetector **63** to control their coordinated operation.

FIG.6 illustrates a geometrical relationship between waveguide hologram **14*ijk*** in a hologram layer and photodetector array **50**.

The photodetector array pixel quantity $Q_{=}$ in one direction, which is parallel to the hologram rows and data rows, must be $Q_{=} = P_{=}/ p_{=} \geq (q_{=}-1)\, h_{=} / p_{=} + M = [h_{=} (q_{=}-1) + M p_{=}]/ p_{=}$, where:

$P_{=}$ is the linear size of detector array along rows, $P_{=} = (q_{=}-1)h_{=} + Mp_{=}$;

$h_{=}$ is the hologram pitch along a row;

$q_{=}$ is the number of holograms in the row;

$p_{=}$ is the pitch of detector pixels along a row; and

M is the number of pixels of readout data in a data page row.

Respectively, the photodetector array pixel quantity in other direction, which is perpendicular to hologram and data page rows, must be $Q_\perp = Q_\perp / p_\perp \geq h_\perp(q_\perp - 1) / p_\perp + N$, where:

$Q_\perp$ is the linear size of detector array along columns;

$h_\perp$ is the hologram pitch along a column;

$q_\perp$ is the number of holograms in the column;

$p_\perp$ is the pitch of detector pixels along the column; and

N is the number of pixels of readout data in a data page column.

$L_= = (q_= - 1)\, h_= + d_=$ is the linear size of the hologram row in the selected direction. The pitch of data page image pixels is equal to or larger than the detector pixel pitch in which case it is a whole number multiple of it.

FIG.7 illustrates a system for retrieving holographically stored data from a multilayer waveguide carrier utilizing a phase conjugate reference beam **20***. In comparison with **FIG.5,** a conjugate coupler **15*_i_** is used and the photodetector is disposed at conjugate plane **04***.

FIG.8 illustrates a system for superimposed waveguide hologram reading. Holograms from non-parallel rows are read by readout beams **20** and **20′** having an angle • between them. An additional deflector is used in the layer and row access unit to provide the required additional angular deviation of reading beam **20** in a plane which is parallel to layer **11_i_**. For example, it is possible to use a rotated optical plate **35 in** addition to deflector **33** (made as a rotated mirror provided with a rotary actuator controlled by computer through the respective interface).

FIG.9 illustrates a system for encrypted waveguide hologram reading. A multichannel phase spatial light

modulator **41** and cylindrical lens **36** are used respectively for readout beam encoding (encryption) and directing the encoded beam **27*ij*** into waveguide layer **11*i***.

FIG. 10 illustrates a system for waveguide hologram reading by a laser matrix. Laser matrix **37** and optical fibers **38*ij*** are used for forming a separate readout beam for each hologram row. The computer controls each laser of matrix **37** through an interface **65**.

<u>Waveguide hologram recording process and apparatus</u>

Holograms can be recorded as Fourier (or quasi Fourier) or Fresnel holograms of a two dimensional matrix of digital (binary or multilevel) or analog signals. Hologram matrices are recorded on separate layers. Then the hologram layers (and waveguide layers when used separately) and cladding layers are sandwiched together forming an optical contact between them, thus producing the multilayer waveguide holographic data storage carrier.

<u>Fourier (or quasi Fourier) hologram recording</u>

FIG.11 represents a schematic view of a process and apparatus for recording a matrix of waveguide Fourier (or quasi Fourier) holograms in a photorecording layer by using a diffraction grating coupler. A monochromatic light source, such as a laser, generates a beam of coherent radiation that is split into a first (signal) beam **70** and a second beam which is used to form a reference beam **28** by optical means **32**, as shown in **FIG.11**. A signal collimated beam **71** expanded by standard optical means **80**, such as lenses, passes through (or reflects from) a spatial light modulator (SLM) **42**. The data page is displayed by SLM **42**. Computer **60** forms control signals which arrive at SLM **42** through interface **66**. Beam **72**, modulated in amplitude (or phase, or polarization) according to the control signals, is focused at the plane **06** near the photorecording medium **17** by

an optical element (lens) **81** following which it illuminates a local area of the photorecording medium **17**. Thus, this local area is illuminated by an image of the Fourier (or quasi Fourier) transformation function of the data page. The layer of photorecording medium **17** is laminated on an optically transparent hard substrate **18** (for example, glass).

Simultaneously, reference beam **28** is transformed by diffraction grating reference beam coupler **73** into guided reference wave **29**. Wave **29** then illuminates the same local area.

A diaphragm **83** may be located close to the photorecording medium surface for preventing parasitic illumination of the photorecording medium.

The optical system for forming the transformed data page image to be recorded in the medium **17** may be realized by different methods, which depend upon the character of the readout beam as described below:

1) Readout beam is the analog of a reference beam.

In this case, the distance between plane **07** (where the optical element **81** is located) and plane **08** (where the SLM **42** is located) is such that the reconstructed data page image will be located at the same distance from the photorecording medium as the distance from the hologram to the detector plane of the readout device. At the same time, the pitch of data page pixel images must be equal to, or a whole number multiple of the pitch of photodetector pixels. This means, for example, that if the pitch of readout data pixel images at the plane **04** of photodetector **50** (**FIG.6**) is equal to the pitch of pixels displayed by the SLM, then a distance **V** between plane **08** and plane **07** is equal to the

double focus length (**2F**) of lens **81**. **F** is the distance between planes **06** and plane **07**.

Different layers **11*i*** (**FIG.5**) of multilayer holographic carrier **10** are located at different distances **G*i*** (**FIG.6**) from the photodetector plane **04** (**FIG.5**). Therefore, it is necessary to provide a condition: **•F*i* + G*i*** = constant. In this case, reconstructed data images from all layers of the carrier will have an identical scale.

Parallel plate **82** (**Fig.11**) of optically transparent material (or a special phase compensator) is used to compensate for any difference in the optical distance from different layers to the detector plane. The thickness and refractive index of this plate must be such as to provide an optical analog of carrier layers located between given layer **11*i*,** (**FIG.6**) and photodetector plane **04** (**FIG.6**).

2) Readout beam (such as 20*, **FIG.7**) is phase conjugate to the reference beam.

In this case, as shown in **FIG.12,** SLM **42** is in the convergent beam from lens **81** in the immediate proximity of plane **07**.

Note: the readout of these type of holograms does not provide for using any image forming optics between hologram plane **01*i*** (**FIG.6**) and photodetector plane **04** (**FIG.6**).

FIG.13 represents a schematic view, which is the same as in **FIG.11,** except for the use of a random phase mask **43** to provide a more uniform Fourier image distribution in hologram recording plane **05*i*.** It is possible to use a phase spatial light modulator as a phase mask **43.**

<u>Hologram recording procedure</u>

As shown in **FIG.11,** guided reference wave **29** propagates in photorecording film layer **17** as in a waveguide. Simultaneously, the modulated signal beam (Fourier or quasi Fourier image) is directed along the line normal to the photorecording film layer. Holograms are recorded by sequentially shifting the photorecording layer after each recording along a distance in the specified direction which is equal to the pitch size $\mathbf{h}_{=}$ of the holograms to be recorded. Two-coordinate positioner **90** is used to make the shifting and is controlled by computer **60** through interface **67**. The pitch ($\mathbf{h}_{=}$ and $\mathbf{h}_{\perp}$, **FIG.1a,b**) of holograms must be divisible by a whole number of photodetector pixels $\mathbf{p}_{=}$ and $\mathbf{p}_{\perp}$ (**FIG.6**). Recorded holograms are arranged in hologram rows forming a matrix in the photorecording layer.

FIG.13 illustrates variants of the recording procedure using a carrier, which contains two different layers: a photorecording (photosensitive) layer **17** and a waveguide layer **19**. In particular, the reference beam is directed into waveguide layer **19** by a prism coupler **86**.

As shown in **FIG.12** and **FIG.14**, the reference beam **28** is directed at a small angle β to the photorecording layer **17**. If the photorecording layer does not have a hard substrate, it is possible to place this layer between optical plates **84** and **85** by using immersion layers **87** and **88** having a refractive index close to that of the photorecording layer.

<u>Fresnel holograms recording</u>

In this case, the readout is to be made by the conjugate reference beam. The recording procedure is the same as described above, but, as shown in **FIG.15**, optical elements, such as focusing lens **81** and collimating lens **89**, form a Fresnel image of SLM data page **42** in the hologram recording plane **05*i***.

Formation of a diffraction grating to couple the reference beam to the waveguide layer.

Grating coupler **16*i*** (**FIG. 1b**) is recorded by a holographic method on the periphery of the photorecording layer **11*i*** (**FIGS. 1a, 1b**), which is also a waveguide layer, or it is formed on the periphery of separate waveguide layer **13*i*** (**FIGS. 1a, 1b**) by stamping, etching or other known methods.

Superimposed hologram recording

The recording procedure is the same as described above, but as shown in **FIG.16**, at least two superimposed hologram **91** and **91'** are recorded sequentially in the overlapping area with different propagation directions **29** and **29'** of the reference beam in the hologram recording plane **05*i***. A minimum angle • between reference beam directions is necessary to provide the independent readout of holograms by the appropriate readout beam.

Encrypted hologram recording

The recording procedure is the same as described above, but the reference beam is formed by the same method as that used for forming a readout encoded beam **27*ij*** (**FIG.9**).

Accordingly, while this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications of the illustrative embodiments, as well as other embodiments of the invention, will be apparent to persons skilled in the art upon reference to this description. It is therefore contemplated that the appended claims will cover any such modifications or embodiments as fall within the scope of the invention.

WE CLAIM:

1. A multilayer holographic data storage carrier, comprising at least two groups of layers, each group containing:

i) a layer having holograms for keeping data to be stored, said holograms arranged in one or more hologram rows, each of said hologram rows having non-overlapping holograms able to be reconstructed simultaneously by one guided wave,

ii) a waveguide layer provided with a coupler, and

iii) a cladding layer located on the outer surface of said waveguide layer between adjoining layer groups,

wherein each said hologram arranged in said one or more hologram rows is capable of reconstructing focused radiation directed therefrom towards an output surface of said data storage carrier and restricted in its spatial angle in order to provide for the spatial separation of its radiation from that of other reconstructed holograms in a region above said output surface and thereby allowing access to data stored by said hologram.

2. The data storage carrier according to claim 1, wherein when having specified spatial angles of radiation from said holograms, a hologram pitch between adjacent holograms is established so as to provide an intersection of said radiation in an area above said region, and thereby permit the spatial separation of radiation reconstructed by the selected hologram from that reconstructed by adjacent holograms arranged in each of hologram rows.

3. The data storage carrier according to claim 2, wherein said holograms are arranged with an equal hologram pitch between each said hologram in each said one or more hologram

rows, while a similar spatial angle of said radiation is established for all of said holograms.

4. The data storage carrier according to claim 1, wherein when having specified a hologram pitch between adjacent holograms, spatial angles of radiation from said holograms are established so as to provide an intersection of said radiation in an area above said region and thereby permit the spatial separation of radiation reconstructed by the selected hologram from that reconstructed by adjacent holograms arranged in each of said hologram rows.

5. The data storage carrier according to claim 4, wherein said holograms are arranged with an equal hologram pitch between each said hologram in each said one or more hologram rows, while a similar spatial angle of said radiation is established for all of said holograms.

6. The data storage carrier according to claim 1, wherein when having at least two parallel hologram rows to be reconstructed together in any hologram layer, a row pitch between adjacent rows is established so as to provide an intersection of radiation from said reconstructed holograms in an area above said region.

7. The data storage carrier according to claim 1, wherein when having at least two parallel hologram rows each to be reconstructed separately in a hologram layer, the row pitch between adjacent rows is established to be not less than the hologram size in a transverse direction to said hologram row.

8. The data storage carrier according to claim 1, wherein when having at least two non-parallel hologram rows each to be reconstructed separately in a hologram layer, at least two holograms relating to different non-parallel rows are recorded so as to be at least partially superimposed.

9. The data storage carrier according to claim 8, wherein an angle between any two neighbouring non-parallel hologram rows is established to be not less than an angle selectivity of said superimposed holograms.

10. The data storage carrier according to claim 1, wherein said holograms in each hologram layer are recorded to provide focusing of their respective radiation at a specified distance into one of the different planes parallel to the flat output surface of the carrier and disposed in the area of intersection of radiation from said holograms.

11. The data storage carrier according to claim 1, wherein said holograms in each hologram layer are recorded to provide focusing of their respective radiation at one of the different specified distances such that all radiation is focused into one and the same plane parallel to the flat output surface of the carrier and disposed in the area of intersection of radiation from said holograms.

12. The data storage carrier according to claim 1, wherein each said hologram in each hologram layer is recorded to store a two-dimensional pixel pattern of a data page.

13. The data storage carrier according to claim 1, wherein said hologram layer in each of said groups is at the same time said waveguide layer.

14. The data storage carrier according to claim 1, wherein said hologram layer and said waveguide layer in each of said groups are made separately and connected to each other by an optical contact to provide transmission of said guided wave into said hologram layer.

15. A multilayer holographic data storage system, comprising:

a) a carrier having at least two groups of layers, each group containing:

i) a layer having holograms for keeping data to be stored, said holograms arranged in one or more holograms rows, each of said hologram rows having non-overlapping holograms able to be reconstructed simultaneously by one guided wave,

ii) a waveguide layer provided with a coupler, and

iii) a cladding layer located on the outer surface of said waveguide layer between adjoining layer groups,

b) a layer and row access unit for forming and directing a readout beam to a selected layer and, through the respective coupler, thereinto along at least one required row,

c) a hologram access unit in the form of a moving window arranged in said region and intended for separating radiation from any hologram to gain access thereto and block radiation from other reconstructed holograms,

d) a multielement photodetector facing towards the output surface of said carrier, intended for receiving reconstructed radiation from said hologram, disposed at or near a focusing plane of said radiation and optically coupled with a pixel pattern of data stored by said hologram, and

e) a computer having respective interface units connected accordingly with control inputs of said layer and row access unit and said hologram access unit as well as with control inputs and outputs of said photodetector for controlling their coordinated operation and for processing readout data,

wherein each said hologram arranged in said one or more hologram rows is capable of reconstructing focused radiation directed therefrom towards an output surface of said carrier and restricted in its spatial angle in order to provide

spatial separation of its radiation from that of other reconstructed holograms in a region above said output surface and thereby allowing access to data stored by said hologram.

16. The data storage system according to claim 15, wherein when having specified spatial angles of radiation from said holograms, a hologram pitch between adjacent holograms is established so to provide an intersection of said radiation in an area above said region and thereby permit the spatial separation of radiation reconstructed by the selected hologram from that reconstructed by adjacent holograms arranged in each of said hologram rows.

17. The data storage system according to claim 16, wherein said holograms are arranged with an equal hologram pitch between each said hologram in each said one or more hologram rows, while a similar spatial angle of said radiation is established for all of said holograms.

18. The data storage system according to claim 15, wherein when having specified a hologram pitch between adjacent holograms, spatial angles of radiation from said hologram are established so as to provide an intersection of said radiation in an area above said region and thereby permit the spatial separation of radiation reconstructed by the selected hologram from that reconstructed by adjacent holograms arranged in each of said hologram rows.

19. The data storage system according to claim 18, wherein said holograms are arranged with an equal hologram pitch between each said hologram in each said one or more hologram rows, while a similar spatial angle of said radiation is established for all of said holograms.

20. The data storage system according to claim 15, wherein when having at least two parallel hologram rows to be reconstructed together in any hologram layer, the row pitch

between adjacent rows is established so as to provide an intersection of radiation from said reconstructed holograms in an area above said region.

21. The data storage system according to claim 15, wherein when having at least two parallel hologram rows each to be reconstructed separately in a hologram layer, a row pitch between adjacent rows is established to be not less than the hologram size in a transverse direction to said hologram row.

22. The data storage system according to claim 15, wherein when having at least two non-parallel hologram rows each to be reconstructed separately in a hologram layer, at least two holograms relating to different non-parallel rows are recorded so as to be at least partially superimposed.

23. The data storage system according to claim 22, wherein an angle between any of two neighbouring non-parallel hologram rows is established to be not less than an angle selectivity of said superimposed holograms.

24. The data storage system according to claim 15, wherein said holograms in each said hologram layer are recorded to provide focusing their respective radiation at a specified distance into one of different planes parallel to the flat output surface of the carrier and disposed in an area of intersection of radiation from said holograms.

25. The data storage system according to claim 15, wherein said holograms in each said hologram layer are recorded to provide focusing their respective radiation at one of the different specified distances such that all radiation is focused in one and the same plane parallel to the flat output surface of the carrier and disposed in an area of intersection of radiation from said holograms.

26. The data storage system according to claim 15, wherein each said hologram in each said hologram layer is recorded to store a two-dimensional pixel pattern of a data page.

27. The data storage system according to claim 15, wherein said hologram layer in each of said groups is at the same time said waveguide layer.

28. The data storage system according to claim 15, wherein said hologram layer and said waveguide layer in each of said groups are made separately and connected to each other by an optical contact to provide transmission of said guided wave into said hologram layer.

29. The data storage system according to claim 15, wherein a row of data pixel images from each said reconstructed hologram at a receiving surface of the photodetector is aligned along the respective row of pixels of the latter and a pitch of said data pixel images in this direction is established to be equal to, or a whole number multiple of, the photodetector pixel pitch in the same direction.

30. The data storage system according to claim 29, wherein when said pitch of data pixel images is equal to said photodetector pixel pitch, the center of each pixel image is disposed at about the center of the corresponding photodetector pixel.

31. The data storage system according to claim 30, wherein the photodetector is disposed in an area of the intersection of radiation from said holograms and the number of photodetector pixels in said direction is established to cover data pixel images from all said holograms without moving the photodetector in the focusing plane and determined by an expression:

$Q \geq [h\ (q - 1)/p + M]$, where

h - is the hologram pitch,

q – is the number of holograms in the hologram row,
p – is the photodetector pixel pitch,
M – is the number of data pixel images in said direction.

32. The data storage system according to claim 15, wherein said hologram access unit is made as a spatial light modulator having the control input and being intended for modulating intensity (or amplitude) of reconstructed radiation transmitted therethrough.

33. The data storage system according to claim 32, wherein said spatial light modulator is disposed at the output surface of the carrier.

34. The data storage system according to claim 15, wherein said window has the form of a slit aligned transversely to a photodetector pixel row, covering all said hologram rows and having a controllable width depending on the distance of the respective hologram layer from the output surface of the carrier and the specified spatial angle of radiation from the respective reconstructed hologram.

35. The data storage system according to claim 15, wherein said window has a rectangular form aligned by one of its sides along a photodetector pixel row and having a controllable size both in the direction of said photodetector pixel row and in the transverse direction, said controllable size being dependent on the distance of the respective hologram layer from said output surface of the carrier and the specified spatial angle of radiation from the respective reconstructed hologram.

36. The data storage system according to claim 15, wherein said layer and row access unit comprises:

a) a unit for generating and forming a beam of coherent radiation, said unit having a control input designated as the first control input of the layer and row access

unit and connected via said interface unit with the computer;

b) angular deflecting means for deflecting the beam of coherent radiation in a plane perpendicular to said hologram layers and in the plane transverse thereto to gain access to a selected layer and a required hologram row respectively, said angular deflecting means having a control input designated as the second control input of the layer and row access unit and connected via said interface unit with the computer; and

c) an optical element having an input coupled to said angular deflecting means and an output conjugated optically with a coupler of the selected layer and intended for converting angular variations of a deflected beam into parallel shifting of a readout beam at its output and directing the readout beam through said coupler into the selected layer along the required hologram row.

37. The data storage system according to claim 15, wherein said layer and row access unit is made as a set of lasers each having output optics and a control input being the respective control input of the layer and row access unit and connected via the respective interface unit with the computer, said optics being conjugated by optical means with a coupler of the respective hologram layer for directing the readout beam thus produced through said coupler into said respective hologram layer along the corresponding hologram row.

38. The data storage system according to claim 37, wherein said optical means is an optical fiber.

39. The data storage system according to claim 15, wherein when any of said holograms are encrypted, a readout beam is composed of a number of rays having different directions

corresponding to those of the reference rays used for recording the respective encrypted hologram.

40. A method of reading out data stored in a multilayer holographic data storage carrier, comprising:

a) forming a readout beam to be used for gaining access to data stored in the carrier having at least two groups of layers, each group containing:

i) a layer having holograms for keeping data to be stored, said holograms being arranged in one or more of hologram rows, each of said hologram rows having non-overlapping holograms able to be reconstructed simultaneously by one guided wave,

ii) a waveguide layer, and

iii) a cladding layer located on the outer surface of said waveguide layer between adjoining layer groups,

b) directing the readout beam into the waveguide layer of the selected group along at least one hologram rows for gaining access to the selected hologram layer and the required hologram row and reconstructing respective holograms,

c) selecting radiation from one of reconstructed holograms for allowing access to data stored therein, and

d) receiving reconstructed radiation from a selected hologram for processing read out data,

wherein said step of selecting radiation is carried out by spatial separating of radiation reconstructed by the selected hologram from that reconstructed by adjacent holograms arranged in each of said hologram rows, said separating is carried out in a region above an output surface of said carrier due to that each said hologram arranged in each of said one or more hologram rows is capable of reconstructing focused radiation directed therefrom towards said output surface of said carrier and restricted in its spatial angle to provide an intersection

of said radiation from reconstructed holograms in an area above said region, while said step of receiving reconstructed radiation is carried out in said area at or near an focusing plane of said radiation.

41. A method of reading out data according to claim 40, wherein said hologram layer in each of said groups is at the same time said waveguide layer.

42. A method of reading out data according to claim 40, wherein said step of receiving reconstructed radiation is carried out by means of a multielement photodetector disposed in said area at the focusing plane of said radiation and oriented so that a row of data pixel images from each said reconstructed hologram at a receiving surface of the photodetector is aligned along a pixel row of the latter, while the number of photodetector pixels in this direction is established so as to cover data pixel images from all said holograms without moving the photodetector in the focusing plane and determined by an expression:

$$Q \geq h\ (q - 1)\ p + M,$$ where

h - is the hologram pitch,
q - is a quantity of holograms in the hologram row,
p - is the photodetector pixel pitch,
M - is a quantity of data pixel images in said direction.

43. A method of reading out data according to claim 40, wherein the step of spatial separating of radiation reconstructed by the selected hologram is carried out by using a moving window arranged in said region and capable of changing its position and size for transmitting this radiation therethrough and blocking radiation from other reconstructed holograms.

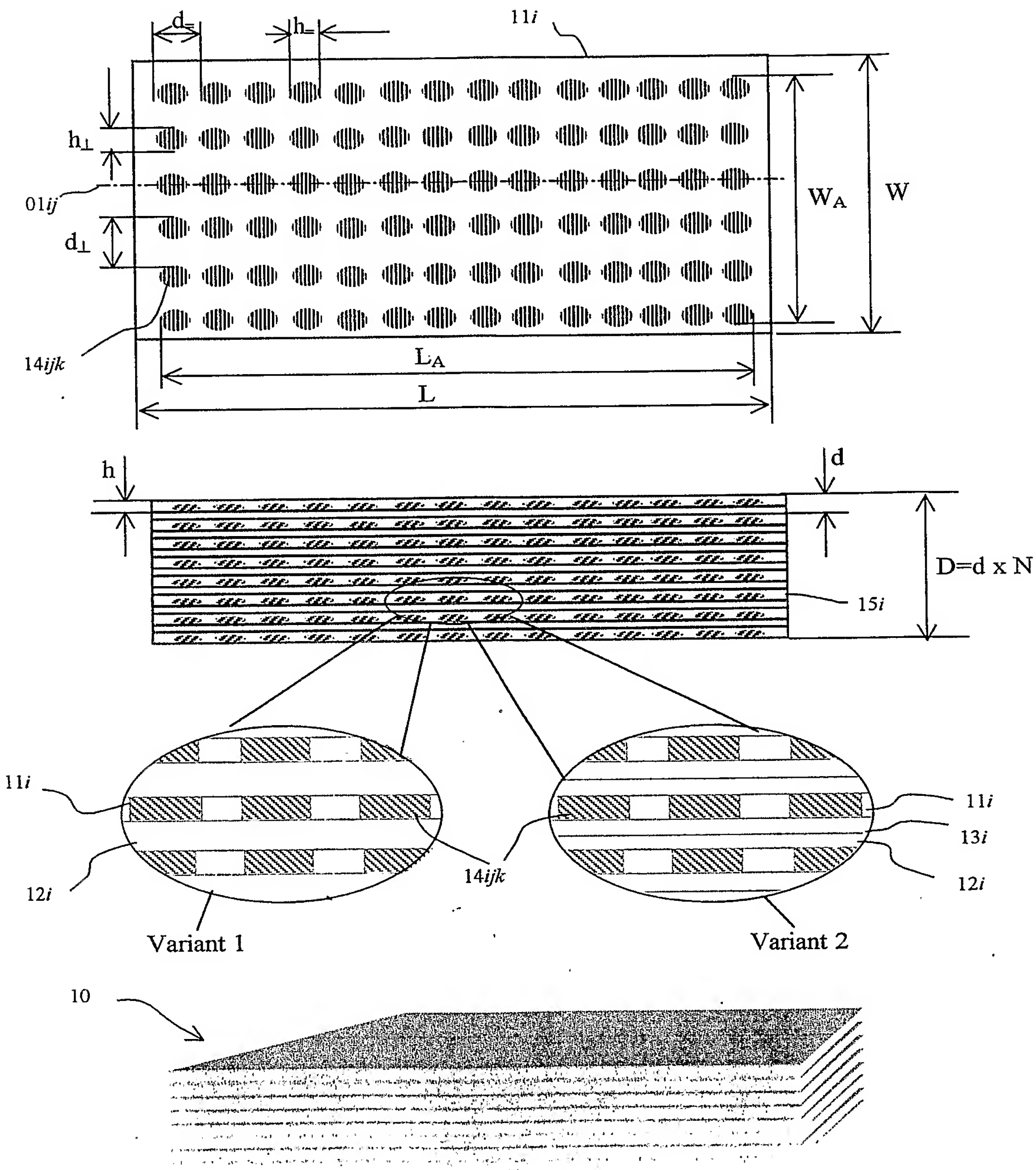
44. A method of reading out data according to claim 43, wherein said window is carried out by means of a spatial

light modulator intended for modulating intensity (or amplitude) of reconstructed radiation transmitted therethrough.

45. A method of reading out data according to claim 43, wherein when using a multielement photodetector for receiving said reconstructed radiation, said window has the shape of a slit aligned transversely to a photodetector pixel row, covering all said hologram rows and having a controllable width depending on the distance of the respective hologram layer from the output surface of the carrier and the specified spatial angle of radiation from the respective reconstructed hologram.

46. A method of reading out data according to claim 43, wherein when using a multielement photodetector for receiving said reconstructed radiation, said window has a rectangular shape aligned by one of its side along a photodetector pixel row and having a controllable size both in the direction of said pixel row and in the transverse direction, said controllable size being dependent on the distance of the respective hologram layer from said output surface of the carrier and the specified spatial angle of radiation from the respective reconstructed hologram.

47. A method of reading out data according to claim 40, wherein when any of said holograms are encrypted, a read out beam is composed of a number of rays having different directions corresponding to those of reference rays used for recording the respective encrypted hologram.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Variant 1
Variant 2
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FIG. 1a

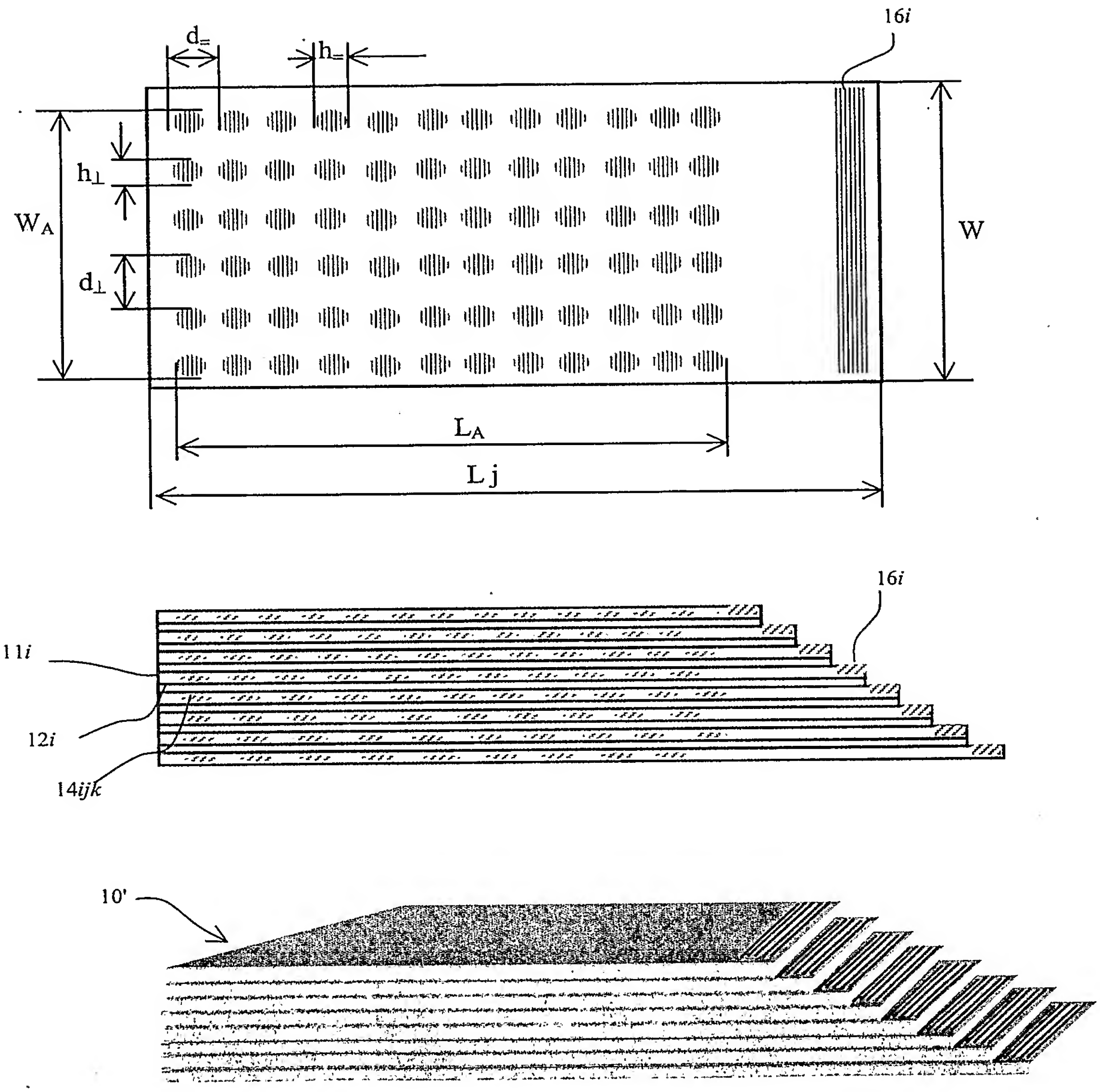


FIG. 1b

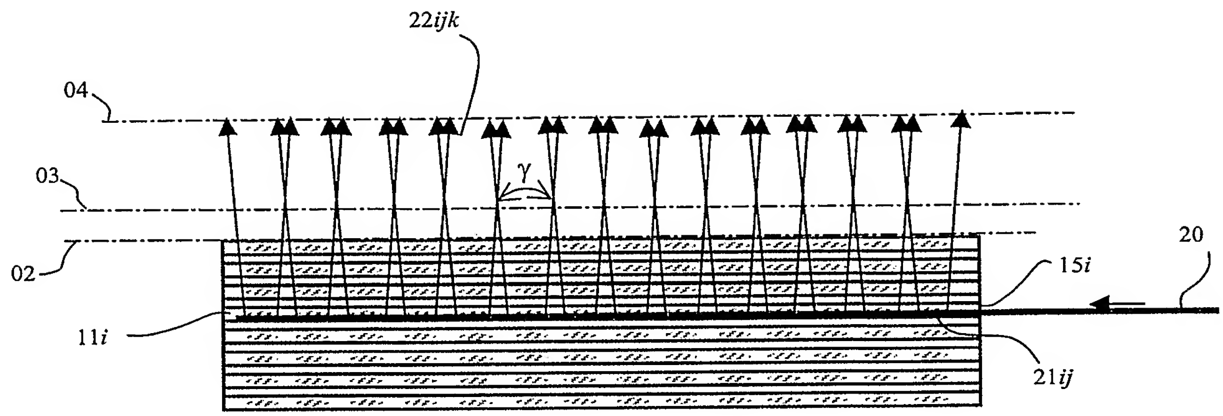


FIG. 2a

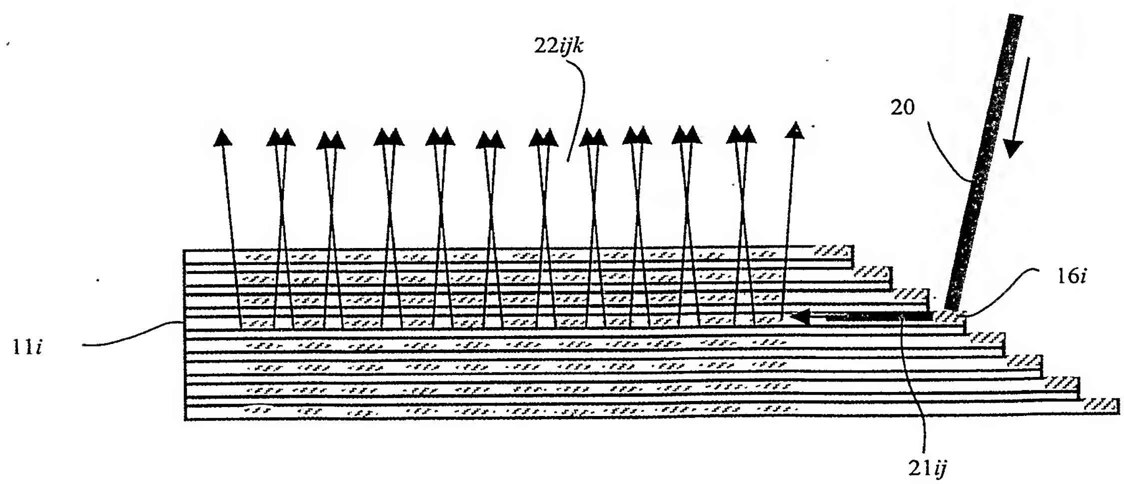


FIG. 2b

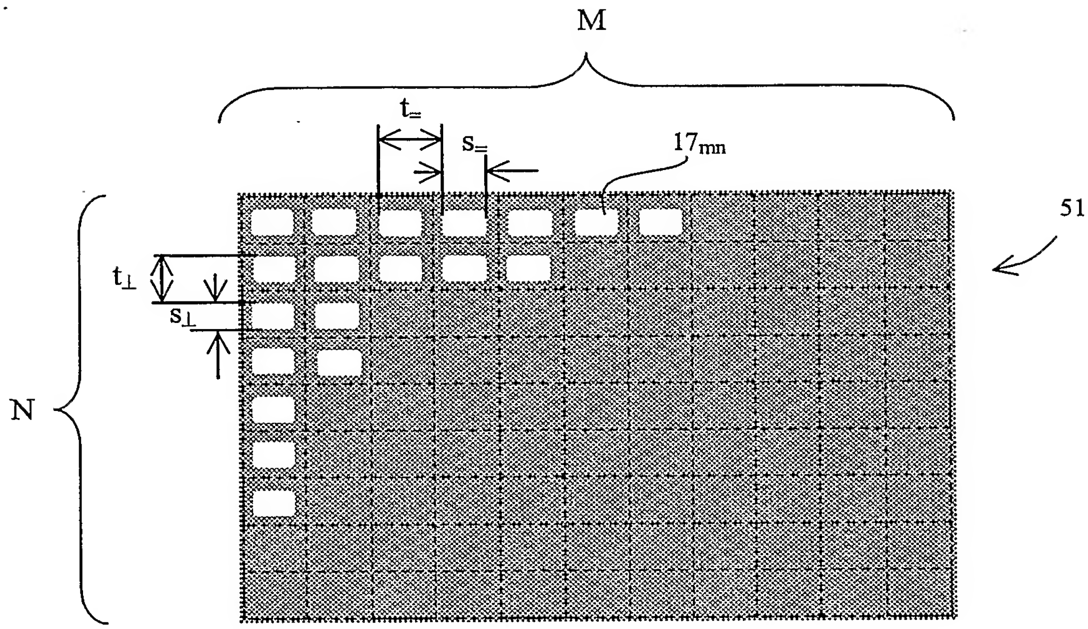


FIG. 3

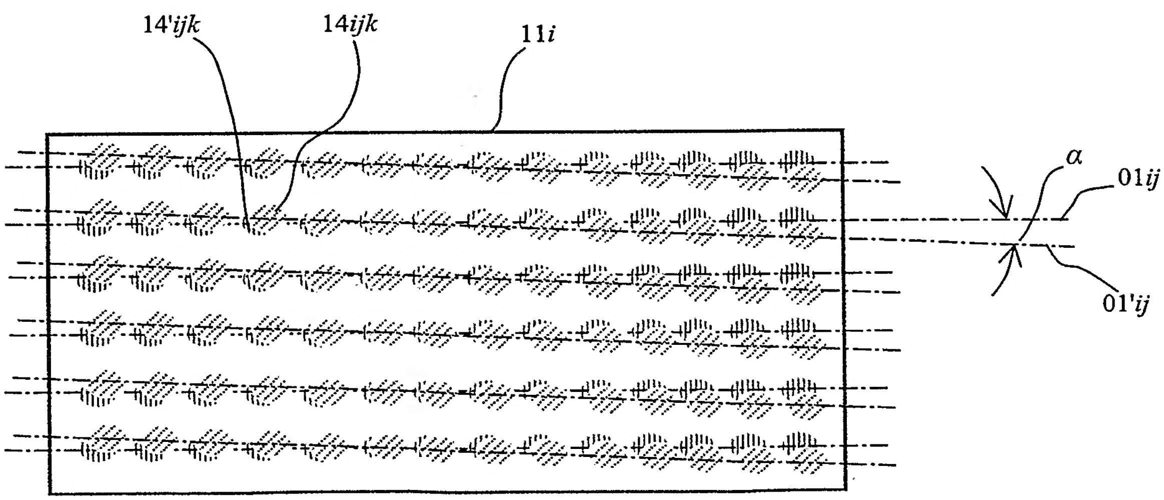
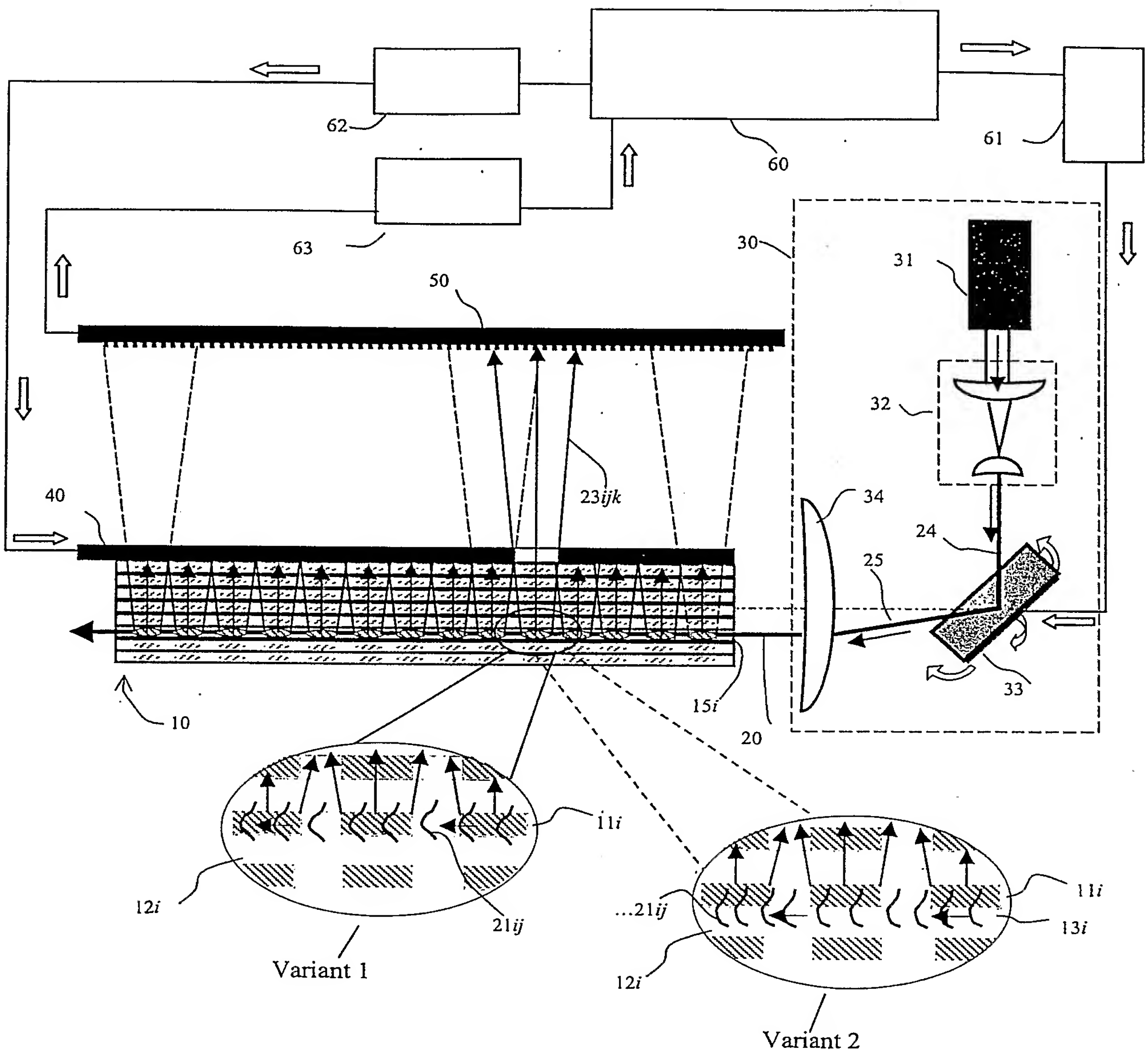


FIG. 4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Variant 1
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12i
Variant 2

FIG. 5

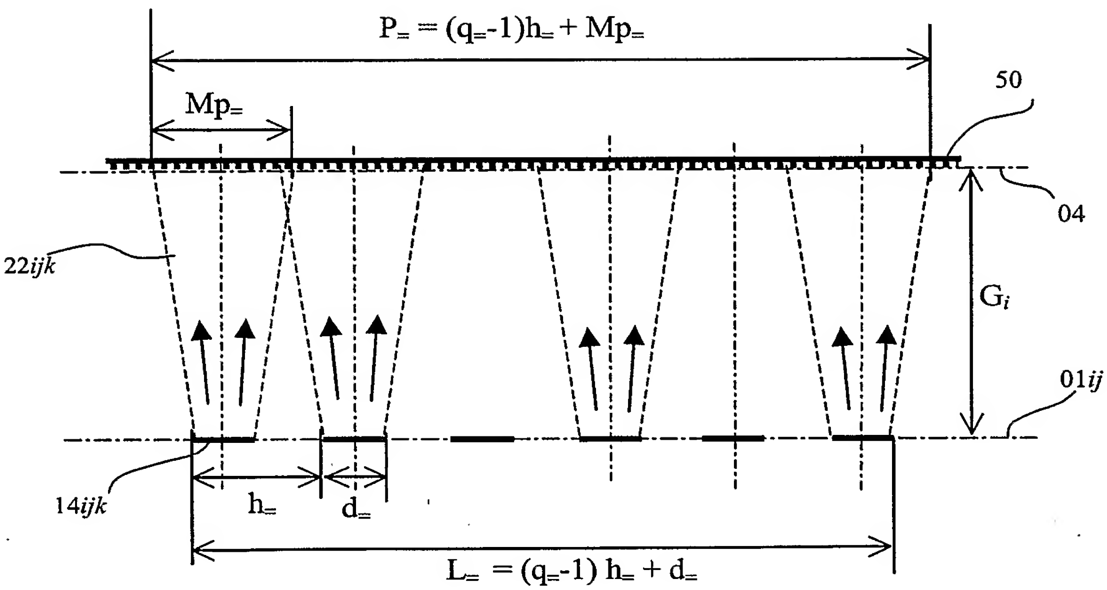

FIG. 6

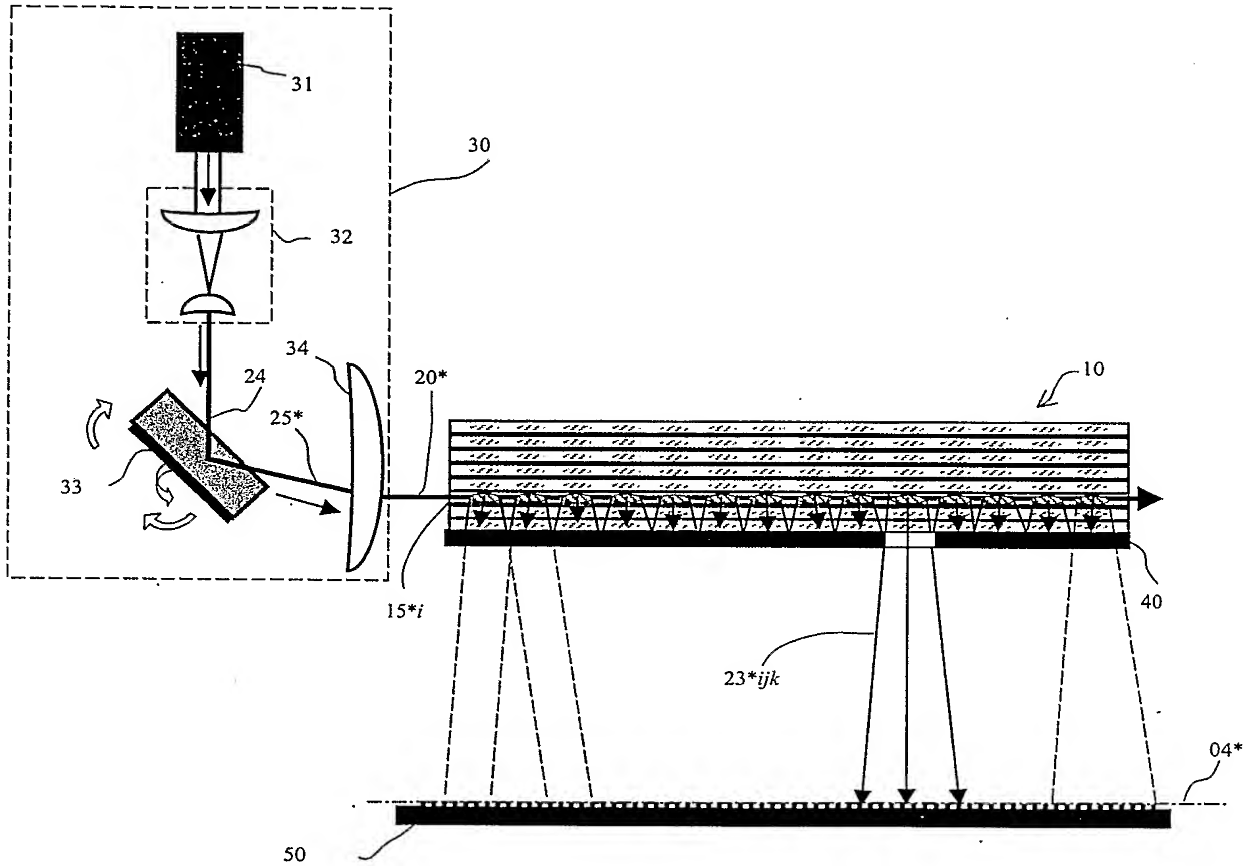

FIG. 7

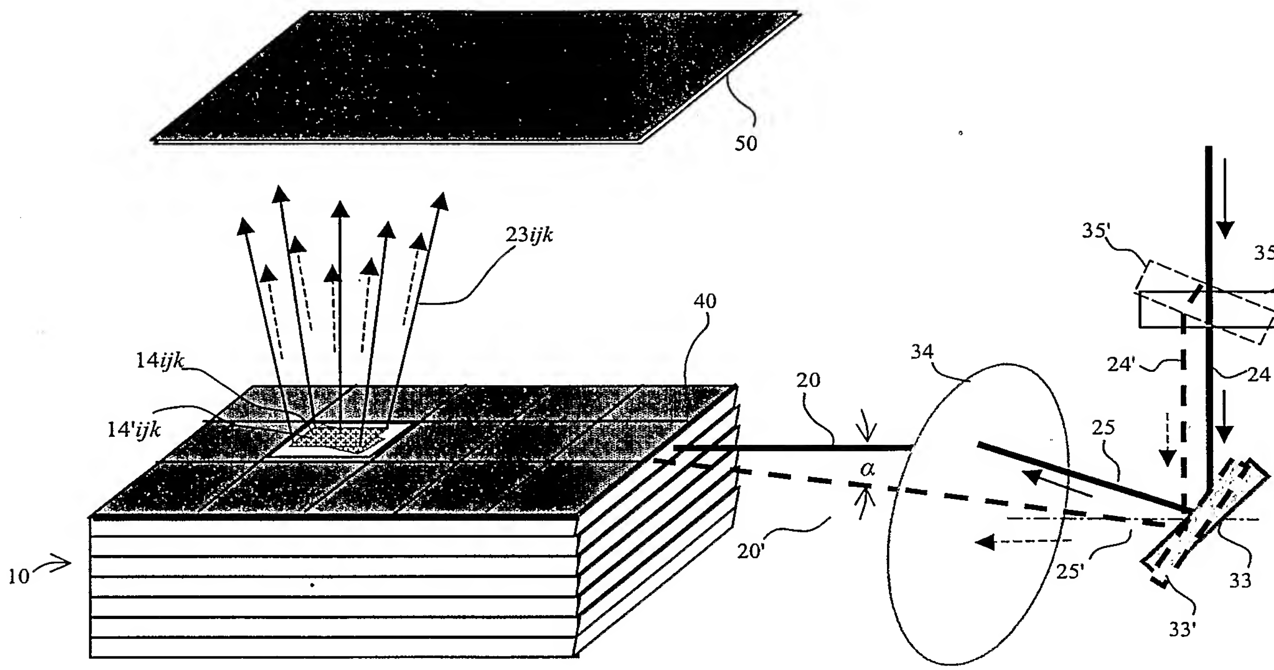

FIG. 8

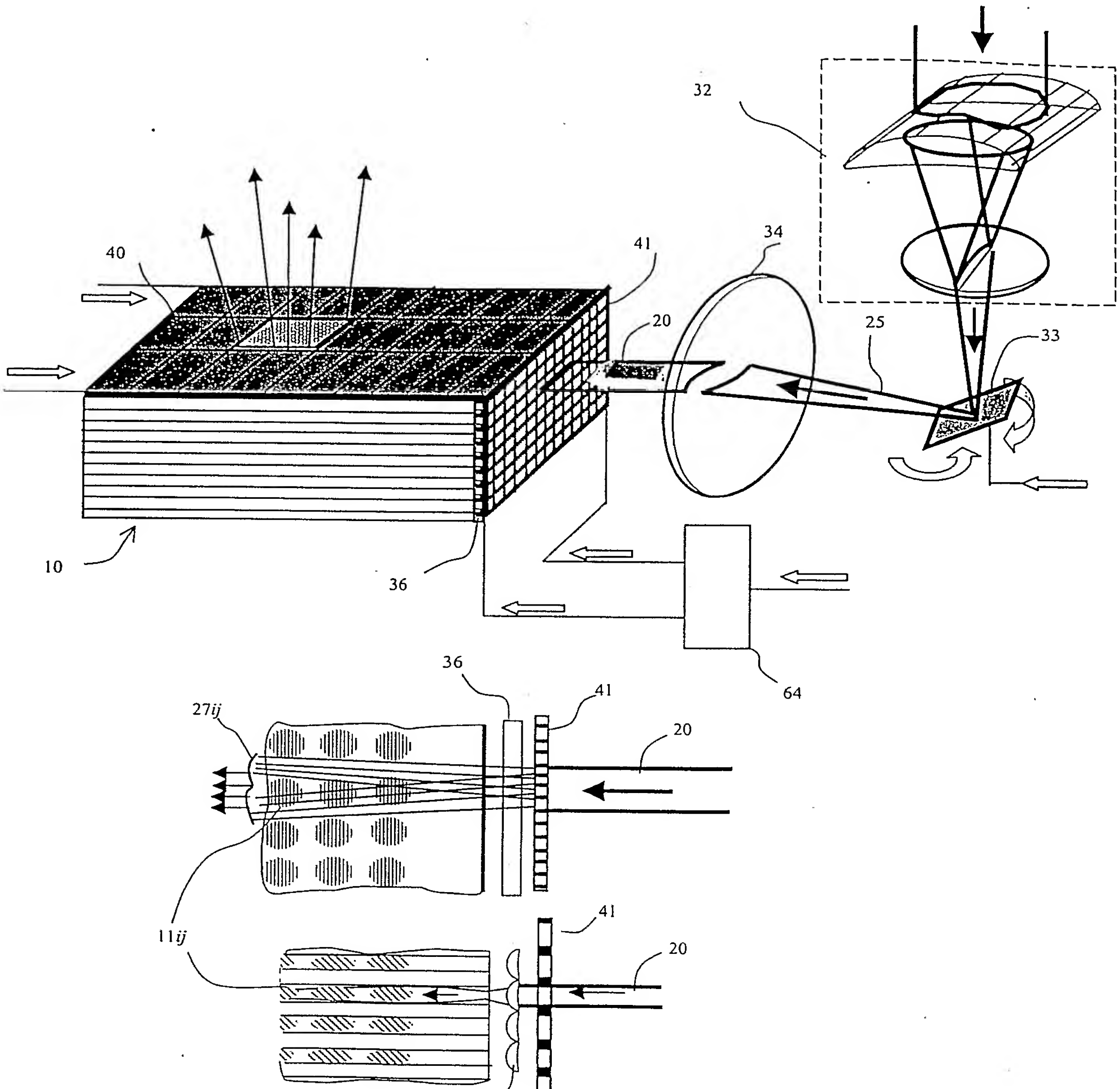

FIG. 9

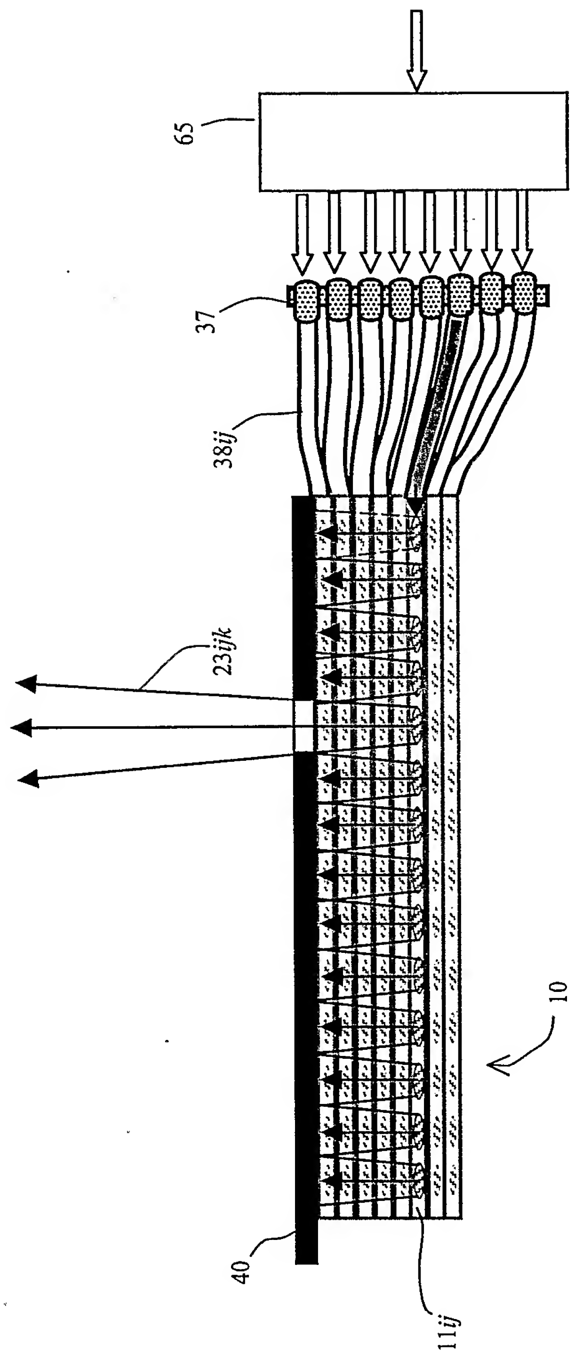

FIG. 10

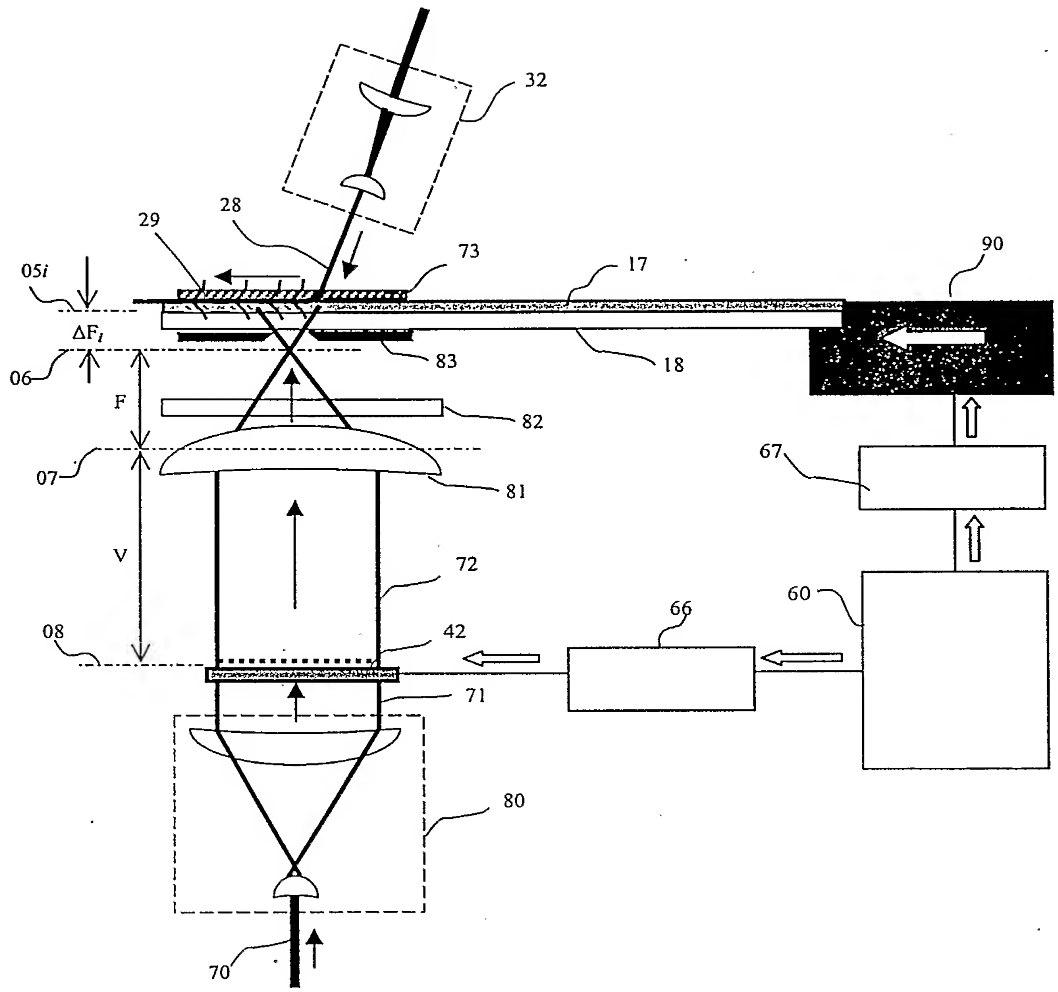
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FIG. 11

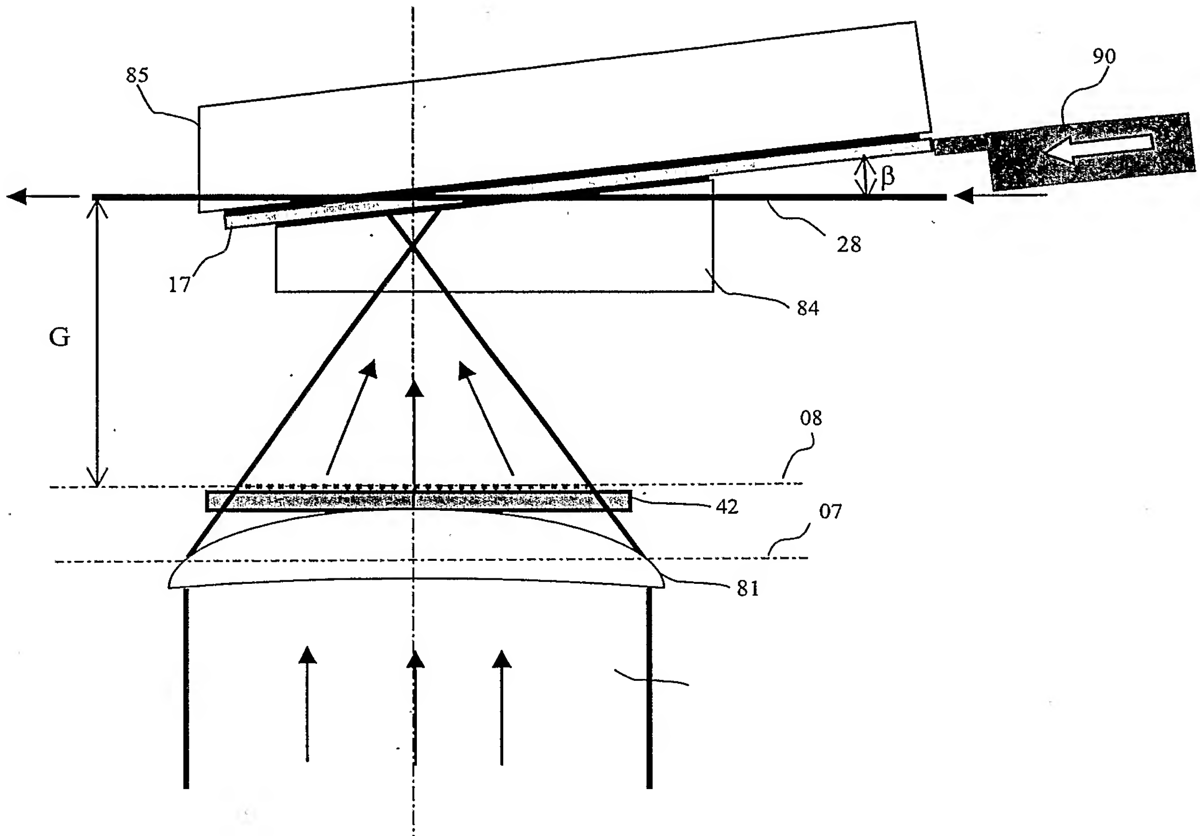

FIG. 12

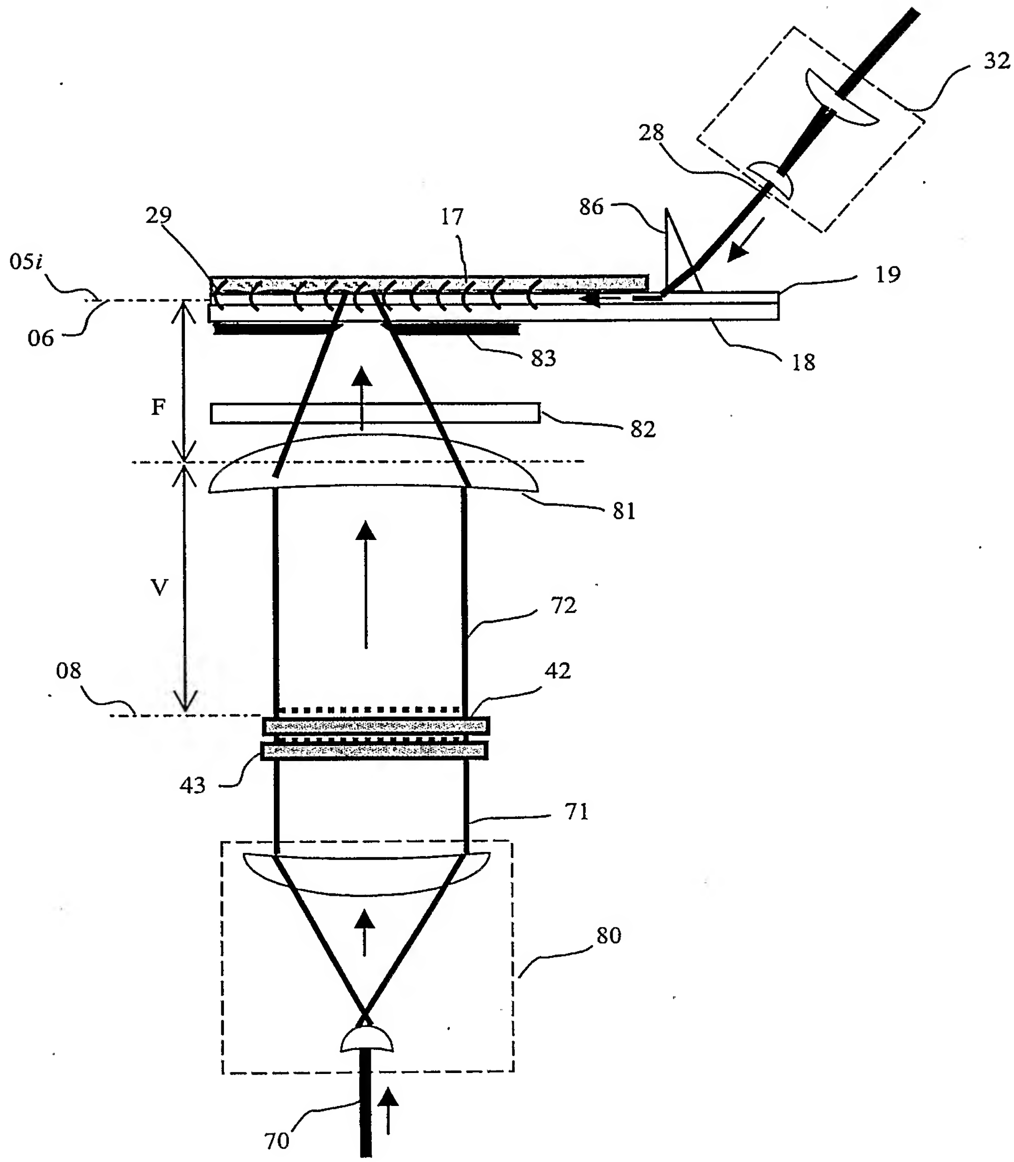

FIG. 13

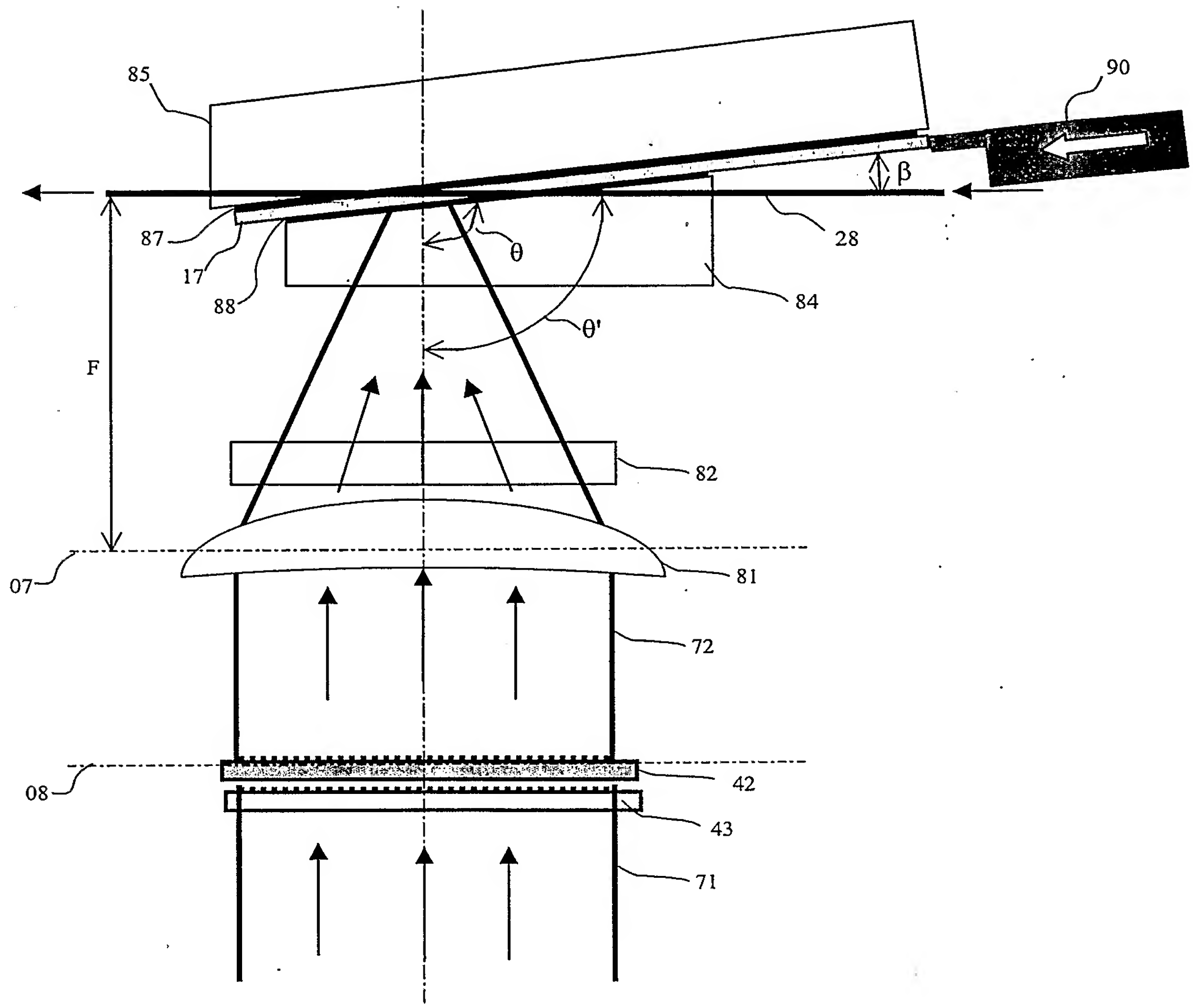

FIG. 14

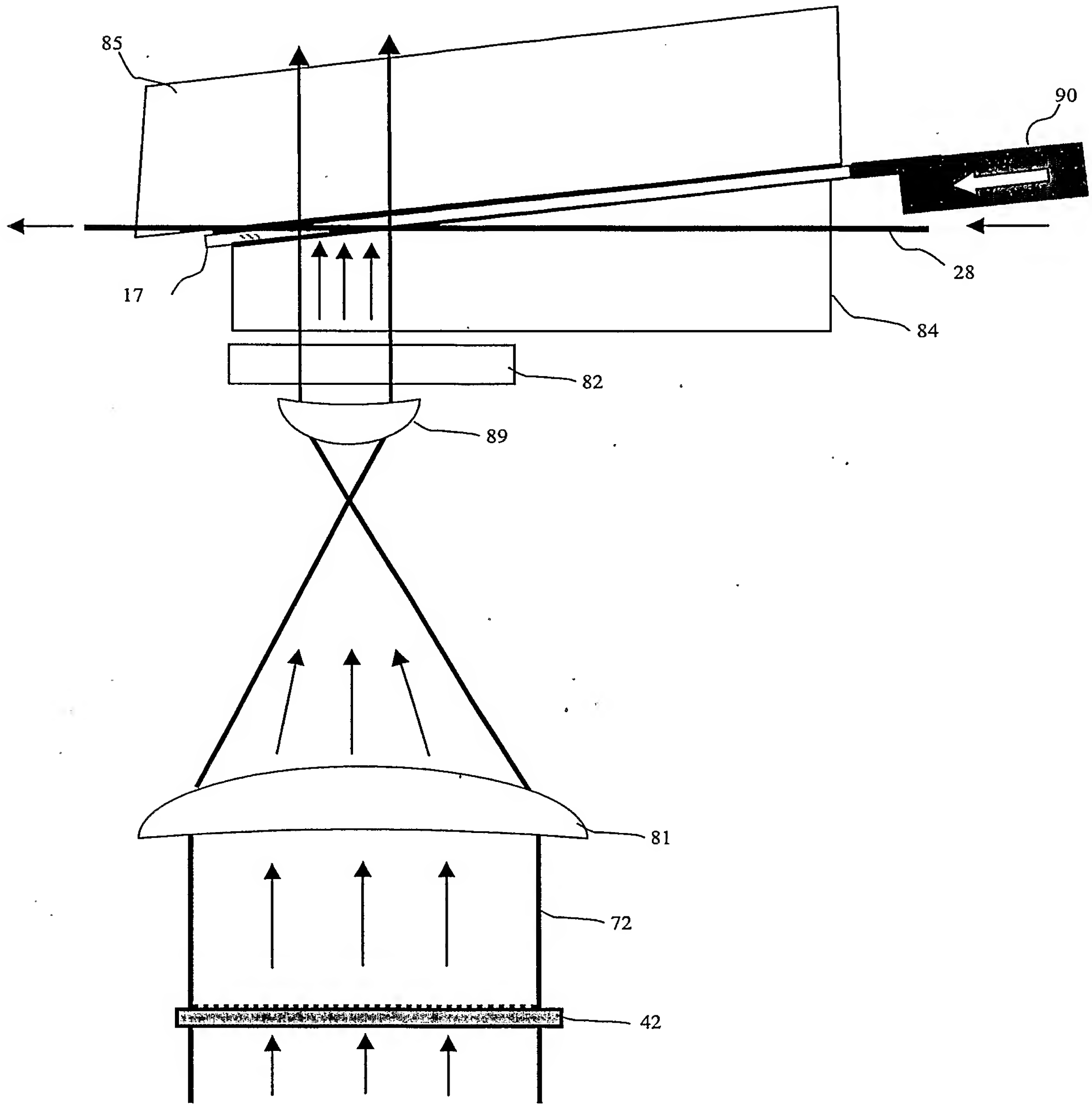

FIG. 15

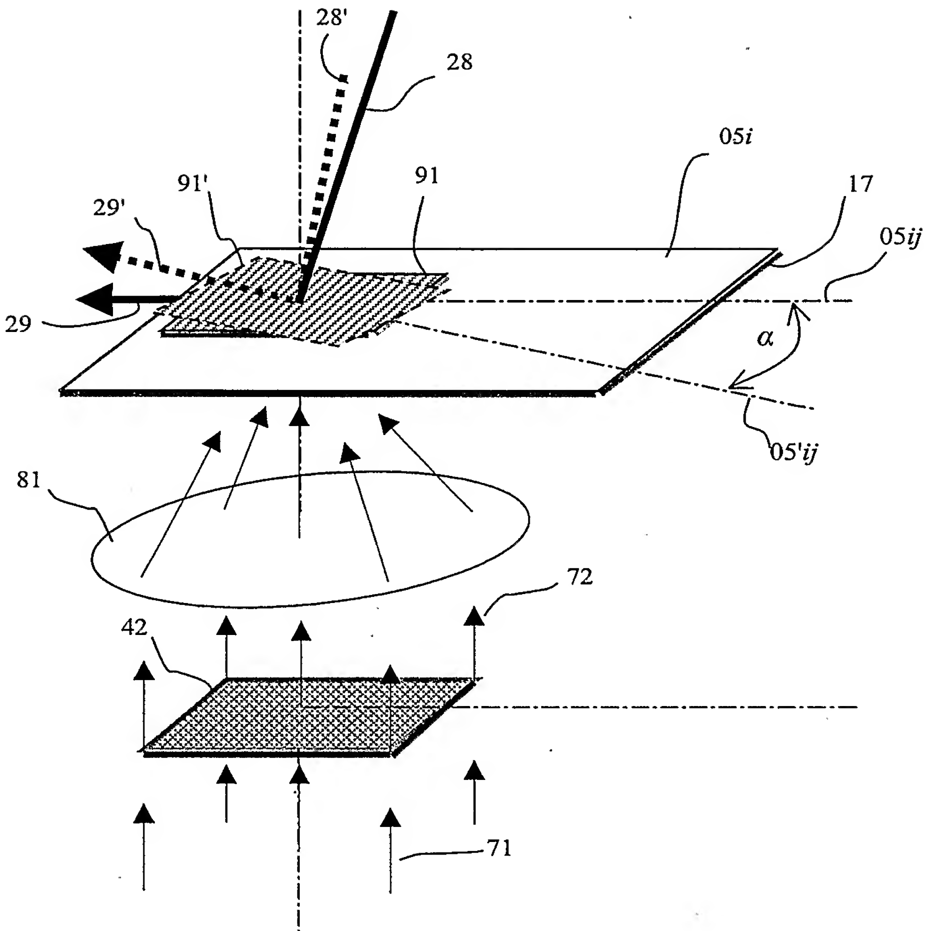

FIG. 16

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 02/01849

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B5/23 G03H1/04 G11B7/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B G03H G11B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, COMPENDEX, INSPEC, IBM-TDB, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 01 57602 A (RAMANUJAM P S ;HVILSTED SOREN (DK); KOPPA PAL (HU); RICHTER PETER) 9 August 2001 (2001-08-09) page 4 -page 16; figures 1,3	1-31, 40-42
Y	the whole document	39,47
Y	US 5 940 514 A (HESSELINK LAMBERTUS ET AL) 17 August 1999 (1999-08-17) the whole document	39,47
A	US 5 465 311 A (CAULFIELD H JOHN ET AL) 7 November 1995 (1995-11-07) the whole document	1-47

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 March 2003	17/03/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Damp, S

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International Application No
PCT/CA 02/01849

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 011, no. 313 (P-626), 13 October 1987 (1987-10-13) & JP 62 103681 A (FUJITSU LTD), 14 May 1987 (1987-05-14) abstract	1-47

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/CA 02/01849

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
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			AU	3398901 A	14-08-2001
			EP	1254398 A1	06-11-2002
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JP 62103681	A	14-05-1987	NONE		